Research Status and Challenges of Intelligent Recognition of Prefabricated Construction Quality Based on BIM and Machine Vision

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Abstract—Prefabricated construction is widely regarded as a vital pathway to advance the industrialization, decarbonization and digital transformation of the construction sector. Compared with conventional cast-in-situ construction, prefabricated manufacturing transfers most production work to controlled factory workshops, yet on-site assembly quality remains a decisive factor governing structural safety, durability and seismic performance. Traditional quality inspection heavily relies on manual visual check and contact measurement, which suffers from low throughput, strong subjectivity, inconsistent recording and limited coverage of concealed defects. The fusion of Building Information Modeling (BIM) and machine vision offers a promising non-contact intelligent inspection paradigm: BIM provides standardized design benchmarks, dimensional tolerances and component spatial information, while machine vision captures site visual data, extracts defect features and quantifies assembly deviations. This paper systematically reviews recent advances in BIM-machine vision integrated inspection for prefabricated construction. It categorizes mainstream vision algorithms and compares their applicability to three typical defects: assembly joint misalignment, rebar layout irregularity and concrete cover thickness non-compliance. This study identifies core bottlenecks including poor scene generalization, virtual-physical domain mismatch, high computing overhead and lack of unified inspection standards. Differing from existing review papers that merely list algorithm achievements, this work proposes a lightweight decoupled inspection framework and highlights small-sample transfer learning as a feasible route for field deployment. The findings are expected to provide theoretical references and actionable directions for future research on digital construction quality control.

Index Terms— Digital Construction; BIM; Machine Vision; Prefabricated Construction; Quality Inspection; Defect Detection

1. Introduction

1.1 Research Background

The global construction industry is under dual pressure of carbon reduction and productivity upgrading. Prefabricated construction reduces on-site wet operation, cuts construction waste and shortens project duration, which aligns with the global pursuit of sustainable infrastructure. In China, the promotion of prefabricated buildings has been incorporated into the national new urbanization and dual-carbon strategy, with a growing number of residential, public and municipal projects adopting precast concrete components, modular units and prefabricated steel structures.

Quality control has always been the bottleneck restricting the further popularization of prefabricated buildings. The quality risks of prefabricated systems are concentrated in two stages: factory fabrication accuracy and on-site assembly precision. Typical defects include excessive joint gaps, dislocation between adjacent panels, uneven rebar spacing, missing steel bars and insufficient concrete cover. These defects are not trivial cosmetic problems. Improper assembly joints weaken waterproof performance and structural integrity; misplaced reinforcements reduce bearing capacity and seismic resistance; inadequate concrete cover accelerates steel corrosion and shortens service life.

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For decades, inspectors have used tape measures, calipers and rebar scanners to collect quality data. Manual inspection is labour-intensive and easily affected by fatigue, lighting and personal judgment. Inspection records are scattered on paper forms, making it difficult to trace defects back to component batches and construction crews. With the rapid development of artificial intelligence and spatial sensing, machine vision has gradually become a substitute for human eyes. Combined with BIM, which stores authoritative design information, vision inspection can automatically compare as-built status against as-designed models and generate quantitative deviation reports. Such integrated technology is one of the core components of digital construction.

1.2 Research Significance

The theoretical significance lies in constructing a classified matching logic between defect types and vision algorithms, clarifying the boundary conditions of different algorithms and supplementing the research system of intelligent construction quality control. Most existing reviews focus on algorithm performance under laboratory conditions, while this paper emphasizes the gap between laboratory datasets and real construction environments.

In practical terms, BIM-vision inspection can reduce manual inspection workload, shorten acceptance cycles and realize digital traceability of component quality. Construction enterprises can adopt such technology to stabilize assembly quality and reduce rectification costs. For the whole industry, it helps form standardized intelligent inspection workflows and accelerates the digital transformation of construction supervision.

1.3 Research Content and Innovation

This paper first elaborates the coupling mechanism between BIM and machine vision in quality inspection. Second, it sorts out traditional feature-based vision algorithms and deep learning detection models and compares their advantages and limitations. Third, it analyzes the application status for three representative prefabricated defects. Fourth, it summarizes on-site challenges and puts forward targeted optimization strategies.

Three core innovations are emphasized:

(1) A scenario-oriented algorithm matching principle: instead of general algorithm introduction, this paper matches algorithms with specific defect characteristics, guiding engineers to select models according to detection targets rather than blindly pursuing high-precision deep learning models.

(2) A lightweight decoupled BIM-vision framework: separate the static benchmark database (simplified BIM tolerance parameters) from real-time visual inference, reducing the requirement of high-end computing equipment on site.

(3) Highlighting domain adaptation under construction interference: dust, uneven illumination and occlusion are not simple noise; this paper points out that compound noise simulation and on-site small-sample fine-tuning are the key to solving false detection and missing detection.

2. Integration Mechanism of BIM and Machine Vision for Quality Inspection

2.1 Functions of BIM in Prefabricated Quality Control

BIM is a digital information carrier covering the whole life cycle of buildings. In intelligent inspection, BIM undertakes three irreplaceable roles.

First, it establishes the quantitative benchmark. Each precast component in BIM carries geometric dimensions, installation coordinates, rebar layout drawings and tolerance limits specified by design codes. These parameters form the judging criterion for deviation calculation.

Second, it provides spatial registration reference. The unified coordinate system of BIM supports the alignment between point cloud or image data collected on site and the digital model. The Scan-vs-BIM workflow calculates the geometric offset between actual components and design models.

Third, it supports closed-loop traceability. Defect coordinates, deviation values, inspection time and rectification records can be attached to the unique ID of each precast component in the BIM model, forming a traceable quality chain from factory production to completion acceptance.

It is worth noting that the complete BIM model contains abundant semantic information, but most of this

information is redundant for real-time inspection. Heavy mesh models will slow down registration and comparison. Therefore, parameter extraction and model simplification are necessary before vision inspection.

2.2 Principle of Machine Vision Defect Recognition

Machine vision replaces human visual perception with optical sensors and computing algorithms. A standard inspection workflow includes image acquisition, preprocessing, feature extraction, defect classification and quantitative measurement. Industrial cameras, photogrammetry equipment and 3D laser scanners are commonly used data acquisition devices. Image preprocessing removes noise caused by dust, shadow and uneven brightness through filtering, histogram equalization and morphological operation. After feature extraction, the algorithm identifies target edges, rebar contours and joint boundaries, and calculates geometric indexes such as gap width and rebar spacing.

The advantages of machine vision are non-contact measurement, high speed and objective output. It is suitable for batch inspection of precast components in factories and rapid spot-check on assembly sites. Nevertheless, vision systems rely heavily on image quality, and any occlusion or strong light will degrade recognition performance.

2.3 Coupling Logic of BIM and Machine Vision

The integration logic can be summarized as “benchmark storage – field perception – registration comparison – closed-loop management”. Before inspection, inspectors extract tolerance standards and coordinate information from BIM to build the benchmark library. On site, machine vision equipment captures images or point clouds of assembled components. Coordinate transformation and spatial registration map the physical data to the BIM coordinate system. The system automatically calculates deviation values, judges whether defects exceed specification limits, marks defect positions and feeds inspection results back to the BIM model for rectification tracking.

This integration breaks the information barrier between design and construction. In the traditional mode, design drawings and site acceptance records are independent. The BIM-vision system realizes the digital connection between design intention and physical construction.

3. Research Status of Mainstream Machine Vision Algorithms

Two branches of vision algorithms are widely adopted in construction inspection: traditional feature-driven algorithms and deep learning algorithms.

3.1 Traditional Feature-Based Algorithms

Traditional algorithms rely on manually designed features and fixed rules. Typical representatives include Canny and Sobel edge detection, Harris feature matching and ICP/NDT point cloud registration.

Edge detection algorithms detect grayscale mutation pixels to extract component boundaries. They are widely used to measure joint gap width and identify rebar edges. The calculation speed is fast and the hardware requirement is low. However, edge detection cannot distinguish real defect edges from interference edges caused by stains and scratches.

Harris feature detection extracts stable corner points for image alignment. Combined with ICP registration, it matches scanning point cloud data with BIM point cloud. Optimized NDT-ICP registration improves the alignment efficiency of large precast wall panels and steel components.

The obvious merit of traditional algorithms is that they do not require large labelled datasets. The main weakness is poor robustness. Once the background, illumination or shooting angle changes, manually set feature rules fail easily. Traditional algorithms are suitable for stable factory environments rather than complex construction sites.

3.2 Deep Learning Algorithms

Deep learning models automatically learn defect features from labelled datasets. CNN, Faster R-CNN and YOLO series are the most frequently used models.

YOLO is favoured for real-time inspection because of its end-to-end architecture and fast inference speed. One

single image can be input to obtain bounding boxes and categories of multiple defects, which is suitable for on-site mobile inspection. Faster R-CNN achieves higher accuracy for small, concealed defects, though at the cost of slower speed. Segmentation models such as U-Net realize pixel-level segmentation of defect areas, supporting accurate area calculation of cracks and over-limit joints.

Many scholars have introduced attention mechanisms and lightweight network structures to adapt deep learning models to construction scenarios. However, deep learning models face two prominent difficulties: the lack of high-quality labelled prefabricated defect datasets and the domain gap between laboratory clean images and messy site images. Models trained on clean datasets often suffer from false positives and missed detection on site.

4. Intelligent Recognition of Typical Prefabricated Construction Defects

4.1 Assembly Joint Deviation

Assembly joints are the connecting parts between precast panels, beams and slabs. Common defects include excessive gap, dislocation and uneven joint width. Joint defects affect waterproof performance and structural continuity.

Current research mostly uses edge detection or segmentation algorithms to extract joint boundaries. After pixel calibration, the system calculates gap width and compares it with the tolerance value in BIM. For large wall panels, 3D laser scanning and Scan-vs-BIM are adopted to obtain the overall surface morphology and detect dislocation. Laboratory tests show that vision measurement error can be controlled within 1 mm, superior to manual measurement.

The main unsolved problem lies in special joints, such as inclined seams and curved component joints. Complex geometric shapes increase the difficulty of feature extraction. Temporary covering and construction debris also block joint areas and lead to missed detection.

4.2 Rebar Layout Defects

Rebar defects include excessive or insufficient spacing, missing reinforcement and position offset. These defects directly impair the mechanical performance of reinforced concrete components.

Vision systems identify rebar outlines from component surface images or sectional images. Segmentation models separate individual rebar targets, extract central lines and compute spacing. The result is compared with the rebar layout information stored in BIM. Existing studies report that the consistency between vision detection and caliper measurement can reach over 95% under ideal conditions.

When steel bars are densely arranged or partially covered by concrete mortar, mutual occlusion will cause feature overlapping. The algorithm cannot distinguish adjacent steel bars clearly, and the detection accuracy drops sharply.

4.3 Concrete Cover Thickness Defects

Concrete cover protects steel bars from corrosion. Too thin cover accelerates rusting; too thick cover reduces effective cross-section and bearing capacity.

Vision-based cover detection mainly depends on sectional images or endoscopic images. The algorithm identifies the outer surface of steel bars and the outer surface of concrete, calculates the distance between two surfaces and judges compliance according to BIM design requirements. Photogrammetry and point cloud reconstruction are also used to realize non-contact measurement.

This method avoids the low efficiency of traditional rebar scanners. Still, coarse aggregate on concrete surfaces forms messy texture interference, which disturbs the edge extraction of steel bars and restricts measurement precision for tiny thickness deviations.

5. Practical Challenges for On-Site Deployment

5.1 Weak Environmental Robustness of Vision Algorithms

Construction sites are highly dynamic and interferential: illumination changes drastically between sunny days,

cloudy days and twilight; dust, mud and splashed concrete cover component surfaces; stacked materials and temporary supports cause occlusion. Most datasets used for model training are collected under well-controlled laboratory conditions. The distribution difference between training data and real site data causes serious performance degradation. False detection and missing detection become the main obstacles to practical promotion.

5.2 Virtual-Physical Domain Mismatch

BIM models are idealized digital products with smooth surfaces and standard dimensions. Actual precast components inevitably have manufacturing errors, surface pits and colour differences. The virtual domain and physical domain belong to different data distributions. Simple Gaussian noise added in simulation cannot reproduce complex site interference. Such domain mismatch makes the deviation comparison result unreliable.

5.3 High Operation Threshold and Computing Cost

The traditional integrated inspection workflow requires operators to process BIM models, conduct point cloud registration and calibrate coordinate systems. It demands professional knowledge of BIM and computer vision, which is beyond the capability of ordinary site inspectors. Meanwhile, 3D point cloud matching and deep learning inference require high-performance GPUs. Expensive hardware and complicated workflows restrict the popularization on small and medium-sized construction projects.

5.4 Lack of Unified Standards and Data Interfaces

At present, there is no unified industry specification for BIM-vision inspection. Different manufacturers adopt self-defined data formats and defect judgment thresholds. Inspection data cannot be seamlessly imported into different BIM platforms. Moreover, many existing systems only finish defect identification, without linking results to rectification scheduling and acceptance. The quality traceability chain is incomplete.

6. Optimization Strategies and Future Trends

6.1 Transfer Learning and Small-Sample Fine-Tuning

To improve environmental adaptability, transfer learning and small-sample learning should be introduced. Collect site images covering variable lighting, dust and occlusion to build a multi-condition defect dataset. Pre-train the model on public datasets and fine-tune it with a small amount of on-site labelled data. Multi-dimensional compound noise simulation can narrow the gap between virtual training data and real scenes, improving the anti-interference ability of detection models.

6.2 Lightweight Decoupled Inspection Framework

This paper proposes a lightweight decoupled framework. Instead of loading the complete BIM model during inspection, the system extracts tolerance parameters, coordinate benchmarks and component ID information in advance and stores them in a lightweight database. Mobile terminals only undertake image acquisition and real-time vision inference. The heavy model rendering and complex registration work are processed on the back-end server. This mode reduces the requirement of on-site equipment and simplifies operation steps for frontline inspectors.

6.3 Establish Unified Data Interface and Defect Grading Standards

Industry associations and supervision departments can formulate unified data interface standards to realize interoperability between BIM platforms and vision inspection devices. Combined with existing concrete structure acceptance codes, quantitative grading standards for joint deviation, rebar spacing and cover thickness defects should be defined, so that intelligent inspection results can be directly accepted by supervision units.

6.4 Future Development Direction

In the long run, BIM-machine vision inspection will converge with digital twin, augmented reality and the Internet of Things. Digital twin platforms can continuously fuse perception data, realize dynamic quality monitoring and predictive risk warning. AR devices can overlay defect marks and rectification suggestions on the physical

component for workers. The whole inspection system will extend from factory component acceptance and on-site assembly inspection to full-life cycle quality management.

7. Conclusion

Prefabricated construction is an important carrier of construction industrialization and digital transformation. Intelligent inspection based on BIM and machine vision overcomes the inherent drawbacks of manual inspection and provides a new technical path for quality control of prefabricated components. This paper reviews the technical integration mechanism, mainstream algorithms and application status for three typical defects: assembly joint deviation, rebar layout disorder and concrete cover thickness non-compliance.

The review shows that existing algorithms achieve satisfactory detection accuracy under laboratory conditions. However, four major challenges hinder large-scale engineering application: poor environmental robustness, virtual-physical domain mismatch, high computing and operation threshold, and insufficient standardization. Targeted optimization approaches including small-sample transfer learning, lightweight decoupled framework and unified data standard are proposed.

Future research should focus on improving the generalization of vision models under complex construction interference and developing low-cost mobile inspection systems. Continuous breakthroughs in this field will promote the landing of AI+BIM digital quality control and support the high-quality and intelligent development of prefabricated construction.

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